

Special Topics on Basic EECS I

VLSI Devices

Lecture 17

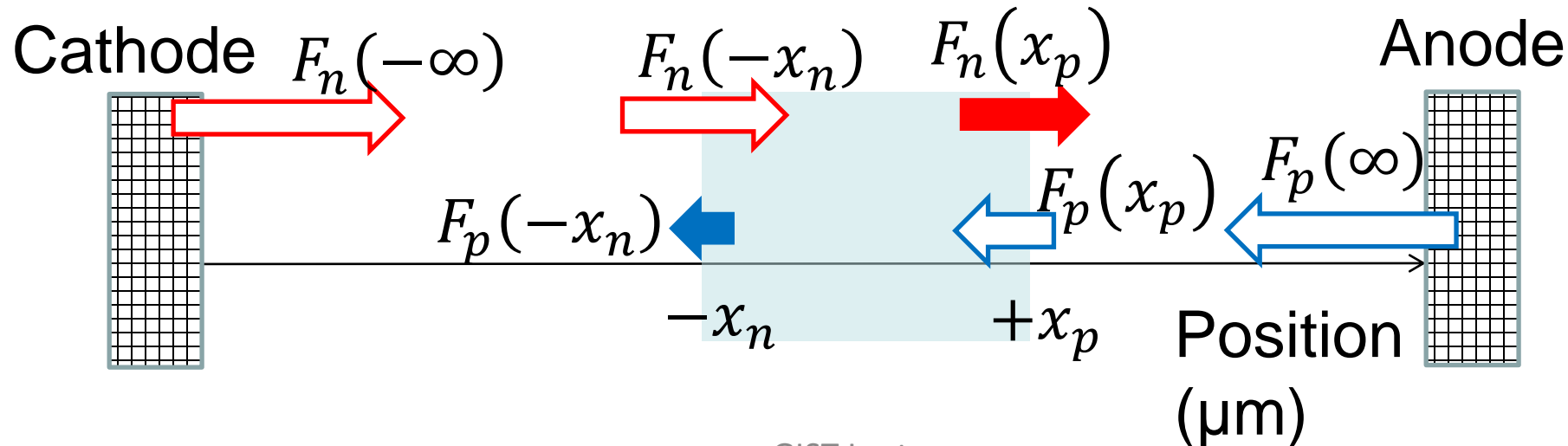
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Recombination

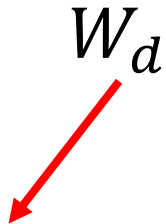
- When the recombination in the depletion region is considered, we can find the following relation:

$$F_p(\infty) = F_n(-\infty) = F_n(x_p) + F_p(-x_n) + \int_{-x_n}^{x_p} [R(x) - G(x)] dx$$



Approximate expression

- We can estimate the upper bound.

$$\int_{-x_n}^{x_p} [R(x) - G(x)] dx < [R(x) - G(x)]_{\text{maximum}} (x_p + x_n)$$


- Assume that $R - G = C N_t \frac{np - n_i^2}{n + p + 2n_i}$ for the SRH centers.
- Also, in the depletion region, $np = n_i^2 \exp \frac{V_{app}}{k_B T / q}$. (Why?)
- Then, we have the maximum value

$$\begin{aligned} [R(x) - G(x)]_{\text{maximum}} &= C N_t \frac{n_i}{2} \left(\exp \frac{V_{app}}{2 k_B T / q} - 1 \right) \\ &= \frac{n_i}{2 \tau_i} \left(\exp \frac{V_{app}}{2 k_B T / q} - 1 \right) \end{aligned}$$

Current

- By using the previous results, the current can be obtained.

$$I_{total} = I_{diode} + I_{SC} \quad \text{Taur, Eq. (2.138)}$$

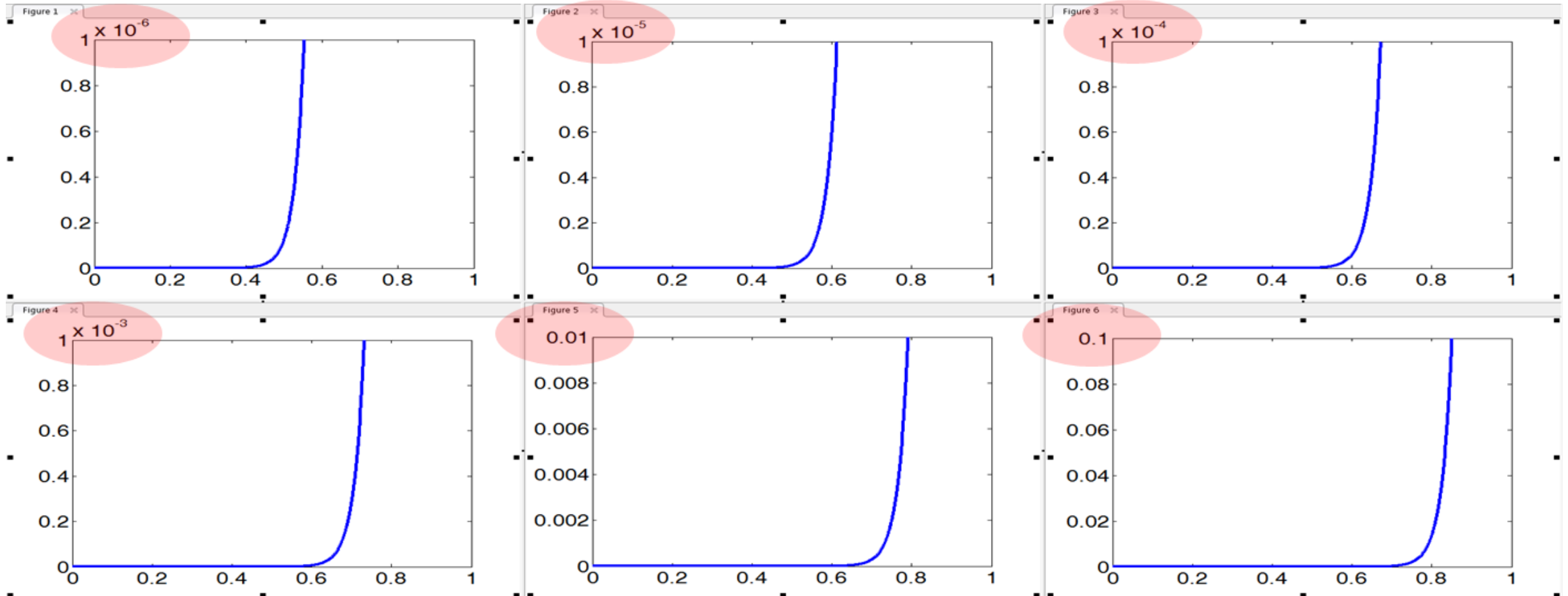
- With the ideal factor, m , the forward diode current is often expressed in the form

$$I_{total} \sim \exp \frac{qV_{app}}{mk_B T} \quad \text{Taur, Eq. (2.139)}$$

- When m is unity, the current is considered “ideal.”
- The nonideality at small forward bias ($m \sim 2$) is caused by the space-charge-region current.

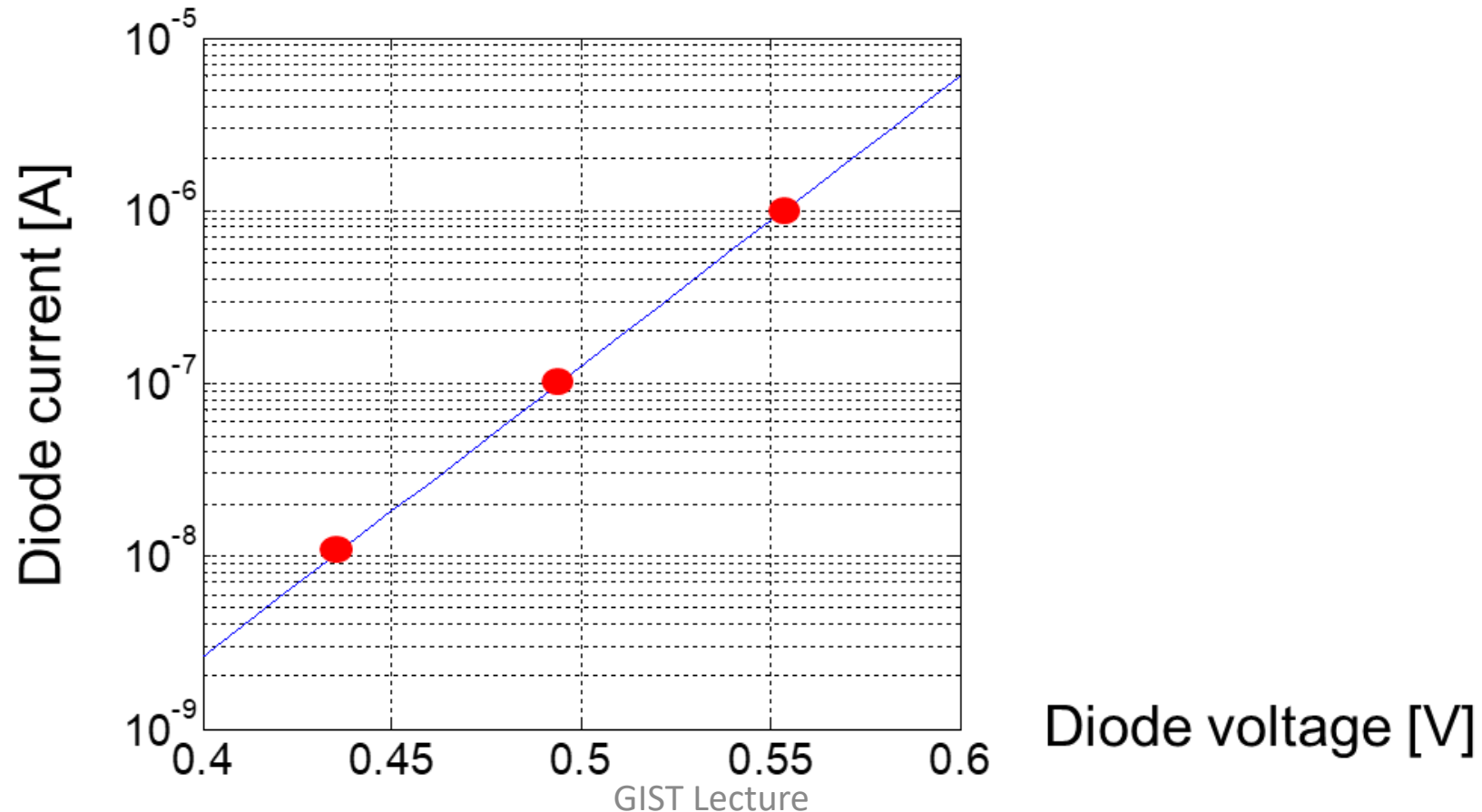
Diode IV curves

- A diode with $I_0 = 5 \times 10^{-16} \text{ A}$ (Only different y scales)



Important observation

- In order to obtain 10x higher current,
 - We must apply only 60 mV additionally. (300 K)



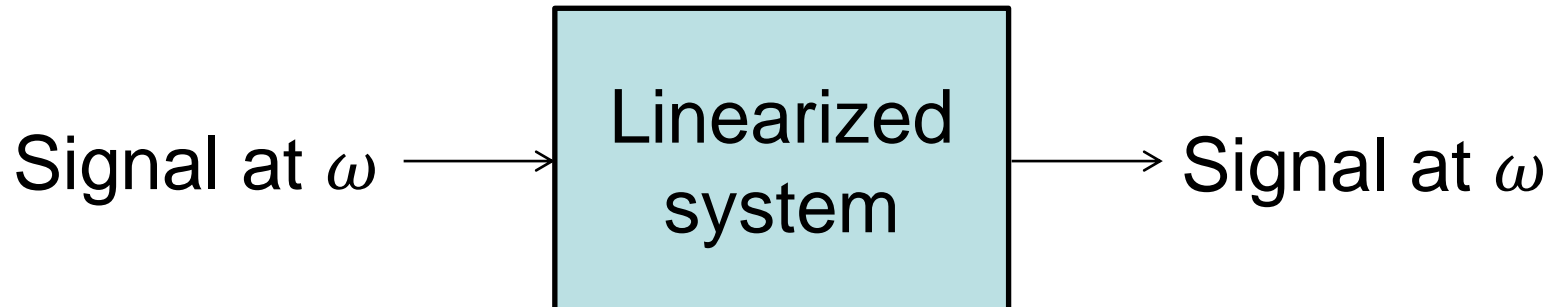
Short diode

- Consider a case where p- and n-regions are shorter than the diffusion length.
 - Our previous solution: $n(x) = n_{p0} \left(\exp \frac{V_{app}}{k_B T / q} - 1 \right) \exp \left(-\frac{x - x_p}{L_n} \right) + n_{p0}$
 - It assumes infinitely long p- and n-regions.
 - Opposite extreme:
$$n(x) = n_{p0} \left(\exp \frac{V_{app}}{k_B T / q} - 1 \right) \left(1 - \frac{x - x_p}{W_p - x_p} \right) + n_{p0}$$

Linearized system

- Our device is nonlinear in general. However, we can linearize it,
 - When signals have small amplitudes.
 - Consider $y = \exp x$.
 - When $x = 24 + 12 \sin \omega t$, how does y look like?
 - When $x = 24 + 0.04 \sin \omega t$, how does y look like?
 - Can you justify the Taylor expansion?

$$y = \exp(x_0 + \delta x) = \exp x_0 \left(1 + \frac{\delta x}{x_0}\right)$$



Switching from OFF to ON

- It takes some time before the diode is turned on and reaches the steady state.
 - Charging up the depletion-layer capacitor
 - Filling up the p- and n-regions with excess minority carriers
- Similarly, when a diode is switched from the ON state to the OFF state, it takes some time before the diode is turned off.

Excessive minority carriers

- (The lightly doped side is often referred to as the *base* of the diode. The other one is called the *emitter*.)

- Total excess minority-carrier charge per unit area

$$Q_B = -q \int_0^W (n_p - n_{p0}) dx \quad \text{Taur, Eq. (2.144)}$$

- For a wide-base diode,

$$Q_B = J_n(x = 0) \tau_n \quad \text{Taur, Eq. (2.145)}$$

- For a narrow-base diode,

$$Q_B = J_n(x = 0) t_B \quad \text{Taur, Eq. (2.146)}$$

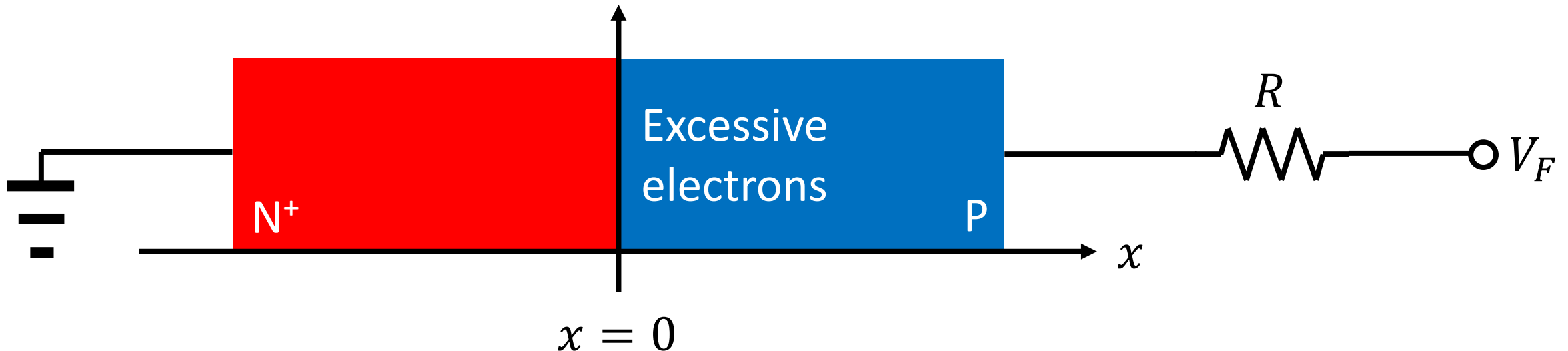
Base-transit time, $\frac{W^2}{2D_n}$



Discharging time of a forward-biased diode

- External voltage changes from V_F to V_R at $t = 0$. Assume that $|V_F|$ and $|V_R|$ are sufficiently higher than 1.0 V.
 - At $t < 0$,

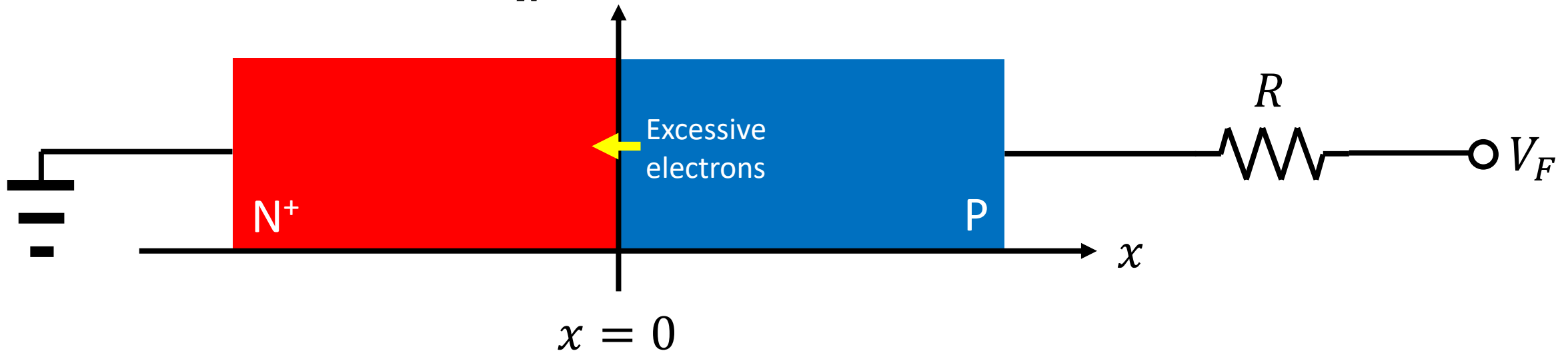
$$I \approx \frac{V_F}{R}$$



Reverse voltage of V_R

- Electrons at the edge of the depletion region are swept away by the electric field in the depletion region towards the n^+ emitter at a saturated velocity.
 - The reverse current is limited by the external resistor,

$$I \approx \frac{V_R}{R} \text{ (Note that it is a negative number.)}$$



Later,

- The reverse current is limited by the diffusion of electrons instead of by the external resistor.
 - Finally, when all the excess electrons removed, the pn diode is completely off.

Thank you!